

# Design of Digital Circuits

## Lecture 1: Introduction and Basics

Prof. Onur Mutlu

ETH Zurich

Spring 2019

21 February 2019

# This lecture is given by

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## **Prof. Onur Mutlu**

<https://people.inf.ethz.ch/omutlu/>

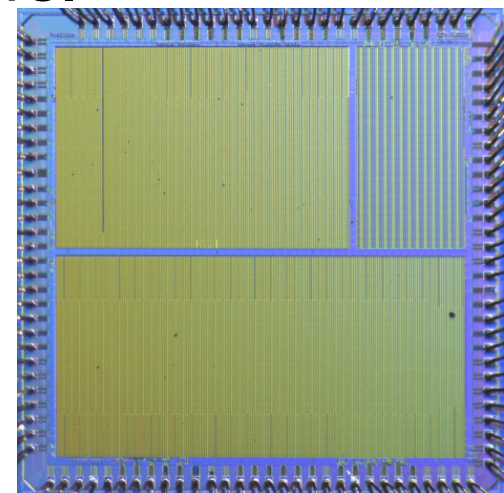
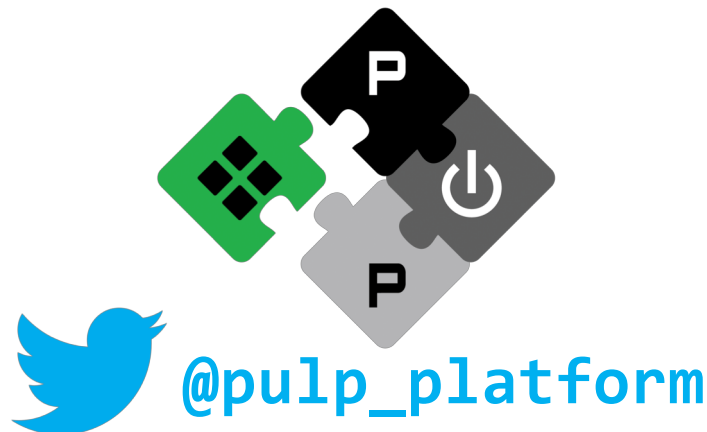
- Prof. at D-INFK (and D-ITET)
- Also Adjunct Prof. at CMU
- Among the most well-known researchers on Computer Architecture
- I just fill in during his absence



# I bring you a bit of EE perspective

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- Frank K. Gürkaynak ([kgf@ee.ethz.ch](mailto:kgf@ee.ethz.ch))
- I work with Prof. Luca Benini at D-ITET
- I design and teach IC Design:
  - We have a Lecture series on VLSI Design (VLSI I, II, III)
  - Supervise and organize practical Semester and Master theses where students design their own Integrated Circuits
- I work on Open Source Hardware, our group works on PULP platform, based on RISC-V processors.



In this lecture we will learn how  
computers work (what's inside)

And today we will discuss:

Why we should care !

# You can blame Gordon Moore

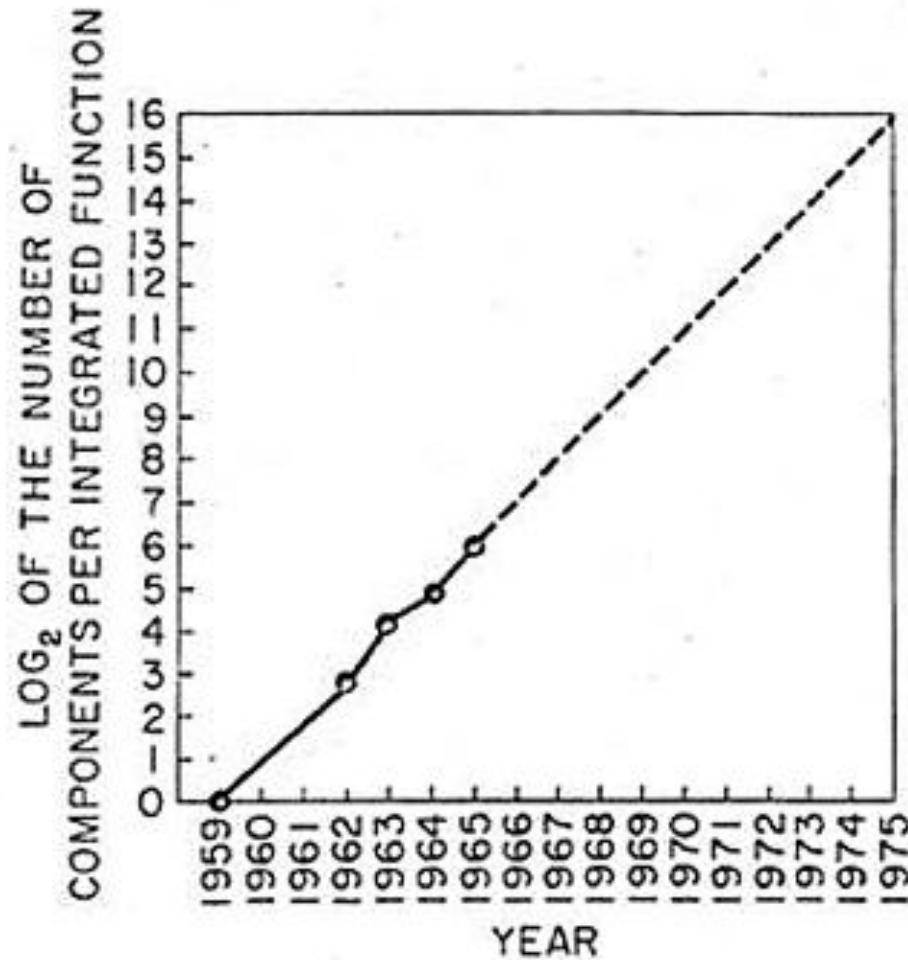


Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.



[https://www.intel.com/pressroom/kits/events/moores\\_law\\_40th/](https://www.intel.com/pressroom/kits/events/moores_law_40th/)

Every other year ICs improve 2x (or so)

- [illegible]



# Meet Samuel and Michael (MSc. D-ITET)

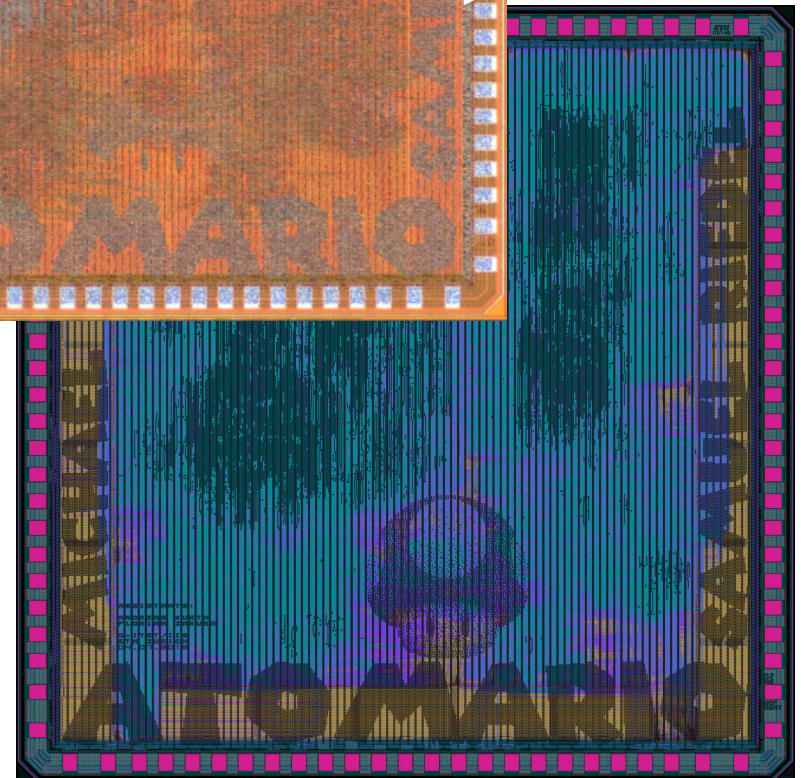
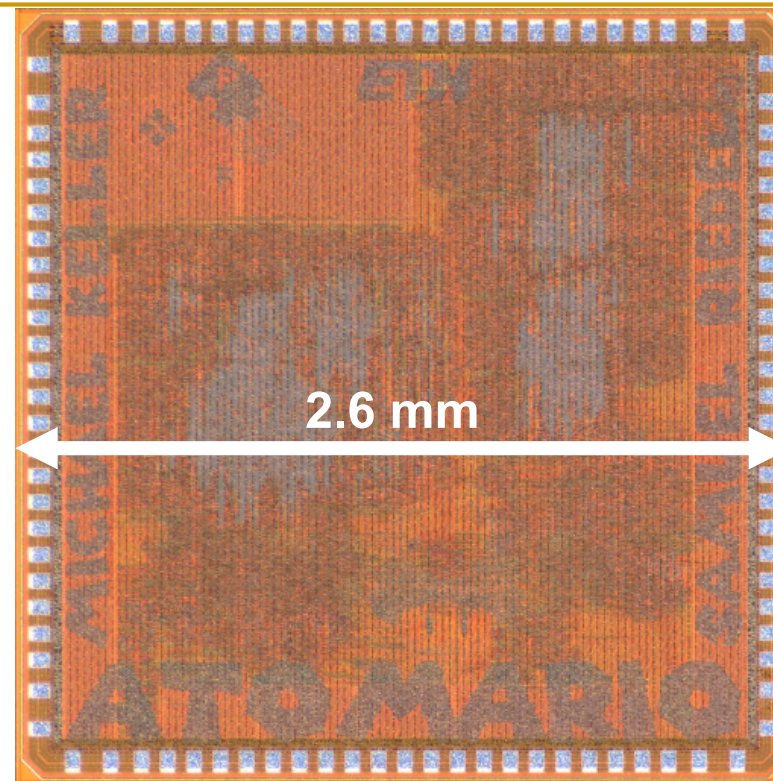
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# Their semester thesis has 10'000'000 trans.

- Atomario has
  - ❑ 8 RISC-V processors
  - ❑ Organized in 2 clusters
  - ❑ Chip in 65nm
  - ❑ Approx 10'000'000 trans.
- Designed by
  - ❑ Two D-ITET students
    - Samuel Riedel
    - Michael Keller
  - ❑ Part of a semester thesis project
    - 14 weeks time
    - 9 ECTS credits
    - .. and they did not even get a **6.00!!**

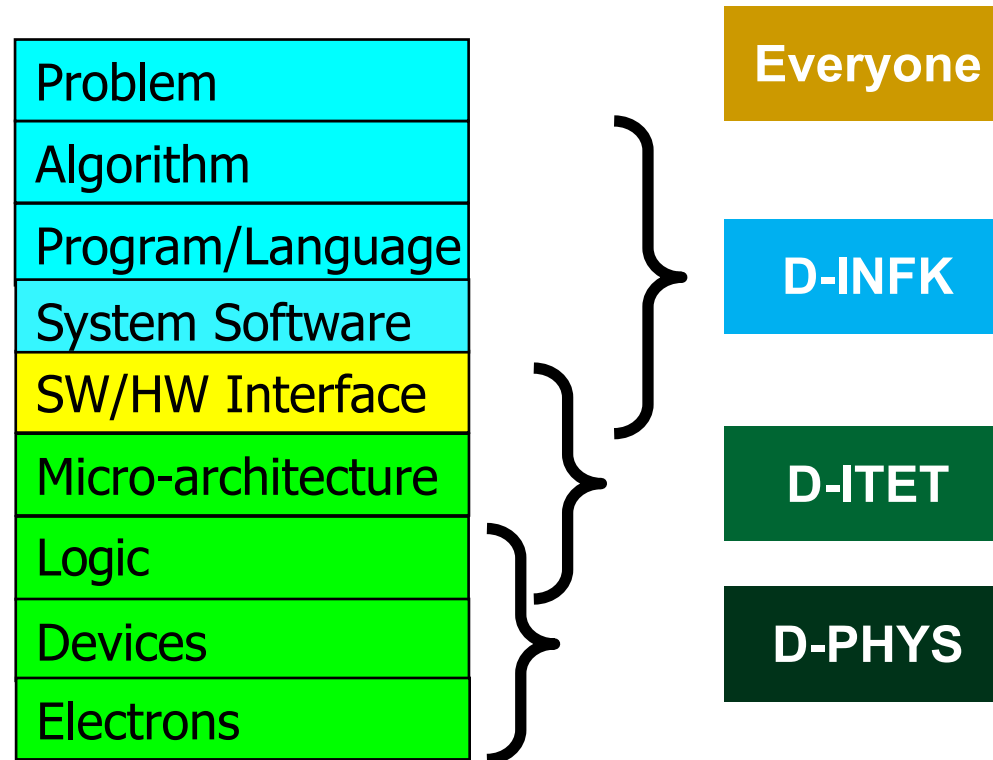


How is it possible that students  
can design such a complex chip?

during their studies, as part of a semester thesis?

# Power of Abstraction

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# The Power of Abstraction

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- Levels of transformation create abstractions
  - Abstraction: A higher level only needs to know about the interface to the lower level, not how the lower level is implemented
  - E.g., high-level language programmer does not really need to know what the ISA is and how a computer executes instructions
- Abstraction improves productivity
  - No need to worry about decisions made in underlying levels
  - E.g., programming in Java vs. C vs. assembly vs. binary vs. by specifying control signals of each transistor every cycle
- Then, why would you want to know what goes on underneath or above?

# Crossing the Abstraction Layers

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- As long as everything goes well, not knowing what happens underneath (or above) is not a problem.
- What if
  - The program you wrote is running slow?
  - The program you wrote does not run correctly?
  - The program you wrote consumes too much energy?
  - Your system just shut down and you have no idea why?
  - Someone just compromised your system and you have no idea how?
- What if
  - The hardware you designed is too hard to program?
  - The hardware you designed is too slow because it does not provide the right primitives to the software?
- What if
  - You want to design a much more efficient and higher performance system?

# Crossing the Abstraction Layers

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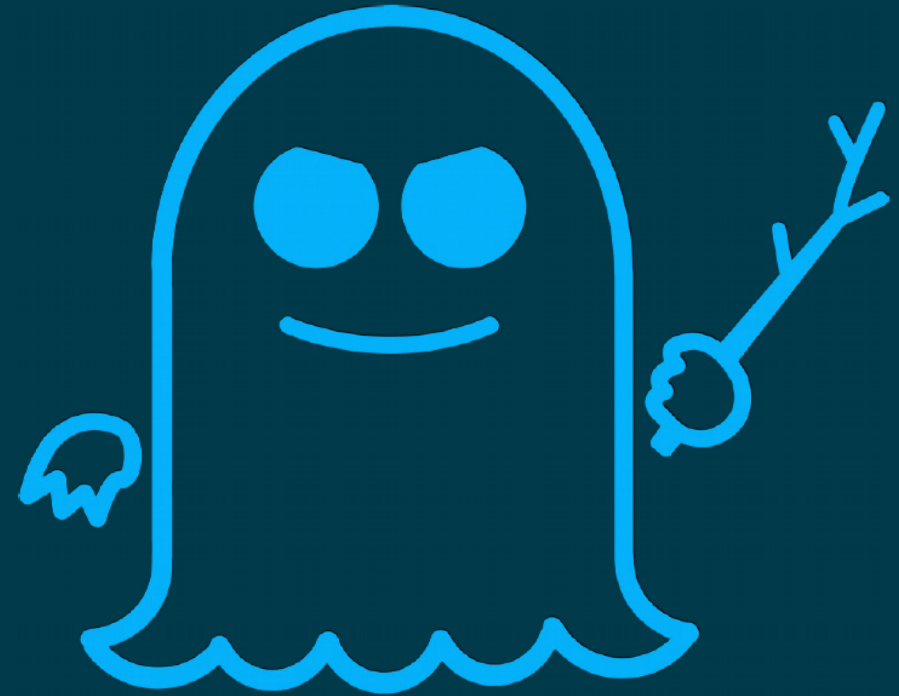
- Two goals of this course (especially the second half) are
  - to understand how a processor works underneath the software layer and how decisions made in hardware affect the software/programmer
  - to enable you to be comfortable in making design and optimization decisions that cross the boundaries of different layers and system components

# Anyone Heard of These?

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**MELTDOWN**



**SPECTRE**

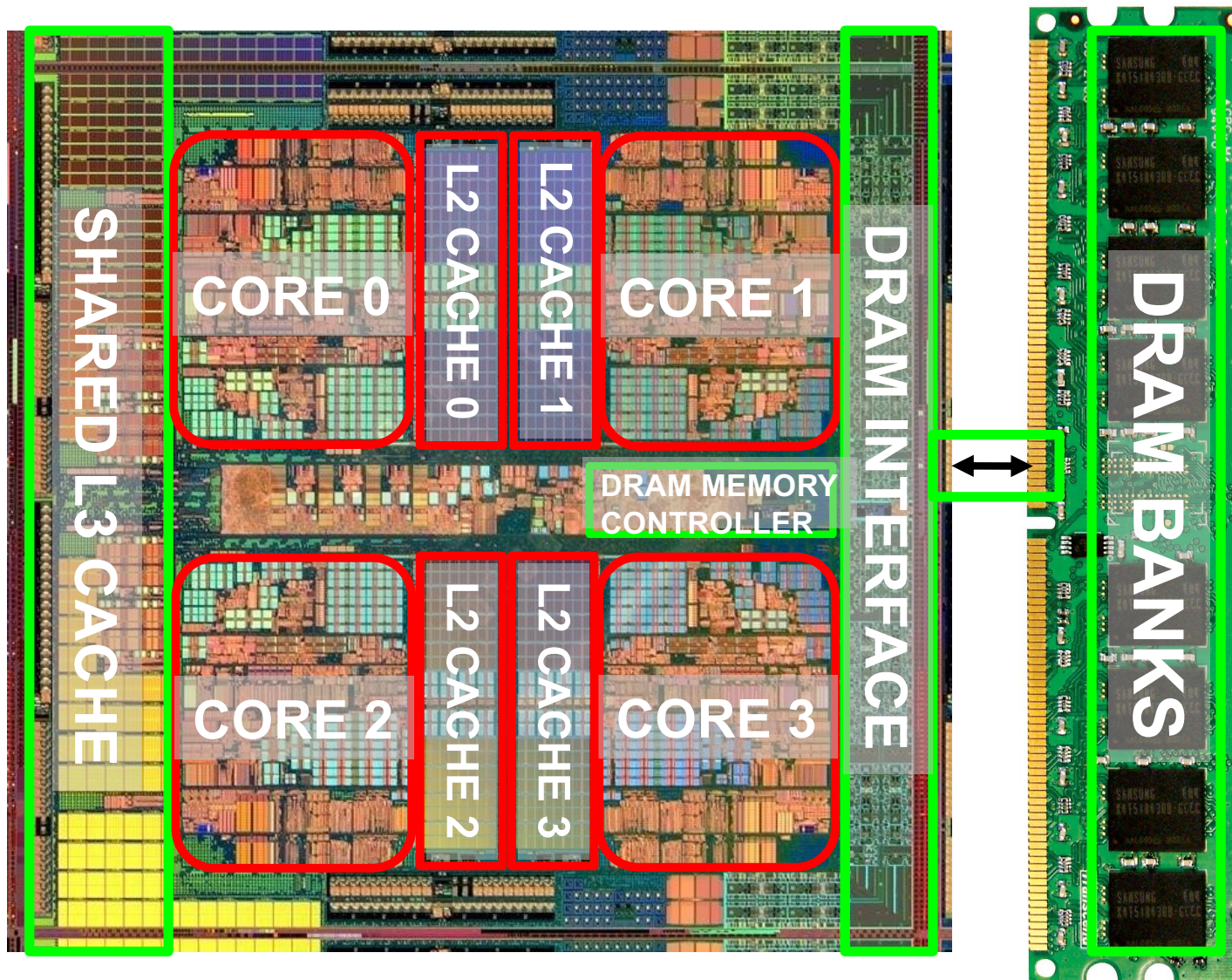
This?





# These? (Multi-Core Systems)

Multi-Core  
Chip



\*Die photo credit: AMD Barcelona

We will talk about these  
tomorrow

Hint: these are issues that you can only solve by  
crossing the abstraction layers.

# Let's Start with Some Puzzles

a.k.a. Prof. Mutlu really likes Architecture



# What Is This?





# What About This?



What Do the Following  
Have in Common?



# Gare do Oriente, Lisbon

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# Milwaukee Art Museum





# Athens Olympic Stadium

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# City of Arts and Sciences, Valencia

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# Florida Polytechnic University (I)

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# Oculus, New York City

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Source: <https://www.dezeen.com/2016/08/29/santiago-calatrava-oculus-world-trade-center-transportation-hub-new-york-photographs-hufton-crow/>

What do All Those Have in Common  
with Bahnhof Stadelhofen?



# Answer: All Designed by a Famous Architect

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- ETH Alumnus, Civil Engineering
- “The train station has several of the features that became signatures of his work; straight lines and right angles are rare.”



**Santiago Calatrava Valls** (born 28 July 1951) is a Spanish [architect](#), [structural engineer](#), [sculptor](#) and [painter](#), particularly known for his bridges supported by single leaning pylons, and his railway stations, stadiums, and museums, whose sculptural forms often resemble living organisms.<sup>[1]</sup> His best-known works include the [Milwaukee Art Museum](#), the [Turning Torso](#) tower in [Malmo](#), Sweden, the [Margaret Hunt Hill Bridge](#) in [Dallas, Texas](#), and the [Museum of Tomorrow](#) in [Rio de Janeiro](#),

# Your First Digital Design Assignment

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- Go and find the closest Calatrava building to this classroom
  - For the ones who like a challenge, find the furthest building that was designed by Calatrava tot his classroom 😊
- Appreciate the beauty & out-of-the-box and creative thinking
- Think about tradeoffs in the design
  - Strengths, weaknesses, goals of design
- Derive principles on your own for good design and innovation
- Due date: **Any time during this course**
  - Later during the course is better
  - Apply what you have learned in this course
  - Think out-of-the-box

# But First, Today's First Assignment

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# Find The Differences of This and That



# This





# That

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# Many Tradeoffs Between Two Designs

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- You can list them after you complete the first assignment...

# Aside: Evaluation Criteria for the Designs

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- Functionality (Does it meet the specification?)
  - Reliability
  - Space requirement
  - Cost
  - Expandability
  - Comfort level of users
  - Happiness level of users
  - Aesthetics
  - Security
  - ...
- 
- How to evaluate goodness of design is always a critical question → "Performance" evaluation and metrics

# A Key Question

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- How was Calavatra able to design especially his key buildings?
- Can have many guesses
  - (Ultra) hard work, perseverance, dedication (over decades)
  - Experience
  - Creativity, Out-of-the-box thinking
  - A good understanding of past designs
  - Good judgment and intuition
  - Strong skill combination (math, architecture, art, engineering, ...)
  - Funding (\$\$\$\$), luck, initiative, entrepreneurialism
  - Strong understanding of and commitment to fundamentals
  - Principled design
  - ...
- (You will be exposed to and hopefully develop/enhance many of these skills in this course)



# Principled Design

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- “To me, there are **two overriding principles** to be found in nature which are most appropriate for building:
  - one is the **optimal use of material**,
  - the other **the capacity of organisms to change shape, to grow, and to move.**”
  - *Santiago Calatrava*
  
- “Calatrava's constructions are inspired by natural forms like plants, bird wings, and the human body.”

# Gare do Oriente, Lisbon, Revisited



Source: By Martín Gómez Tagle - Lisbon, Portugal, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=13764903>

Source: <http://www.arcspace.com/exhibitions/unsorted/santiago-calatrava/>

# A Principled Design

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## Zoomorphic architecture

From Wikipedia, the free encyclopedia

**Zoomorphic architecture** is the practice of using animal forms as the inspirational basis and blueprint for architectural design. "While animal forms have always played a role adding some of the deepest layers of meaning in architecture, it is now becoming evident that a new strand of **biomorphism** is emerging where the meaning derives not from any specific representation but from a more general allusion to biological processes."<sup>[1]</sup>

Some well-known examples of Zoomorphic architecture can be found in the **TWA Flight Center** building in **New York City**, by **Eero Saarinen**, or the **Milwaukee Art Museum** by **Santiago Calatrava**, both inspired by the form of a bird's wings.<sup>[3]</sup>



# What Does This Remind You Of?

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# The Architect's Answer

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## Design [\[ edit \]](#)

Calatrava said that the Oculus resembles a bird being released from a child's hand. The roof was originally designed to mechanically open to increase light and ventilation to the enclosed space. [Herbert Muschamp](#), architecture critic of *The New York Times*, compared the design to the [Bethesda Terrace and Fountain](#) in [Central Park](#), and wrote in 2004:

# Strengths and Praise

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“ Santiago Calatrava's design for the World Trade Center PATH station should satisfy those who believe that buildings planned for ground zero must aspire to a spiritual dimension. Over the years, many people have discerned a metaphysical element in Mr. Calatrava's work. I hope New Yorkers will detect its presence, too. With deep appreciation, I congratulate the Port Authority for commissioning Mr. Calatrava, the great Spanish architect and engineer, to design a building with the power to shape the future of New York. It is a pleasure to report, for once, that public officials are not overstating the case when they describe a design as breathtaking.<sup>[43]</sup>

”



# Design Constraints and Criticism

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However, Calatrava's original soaring spike design was scaled back because of security issues. The *New York Times* observed in 2005:

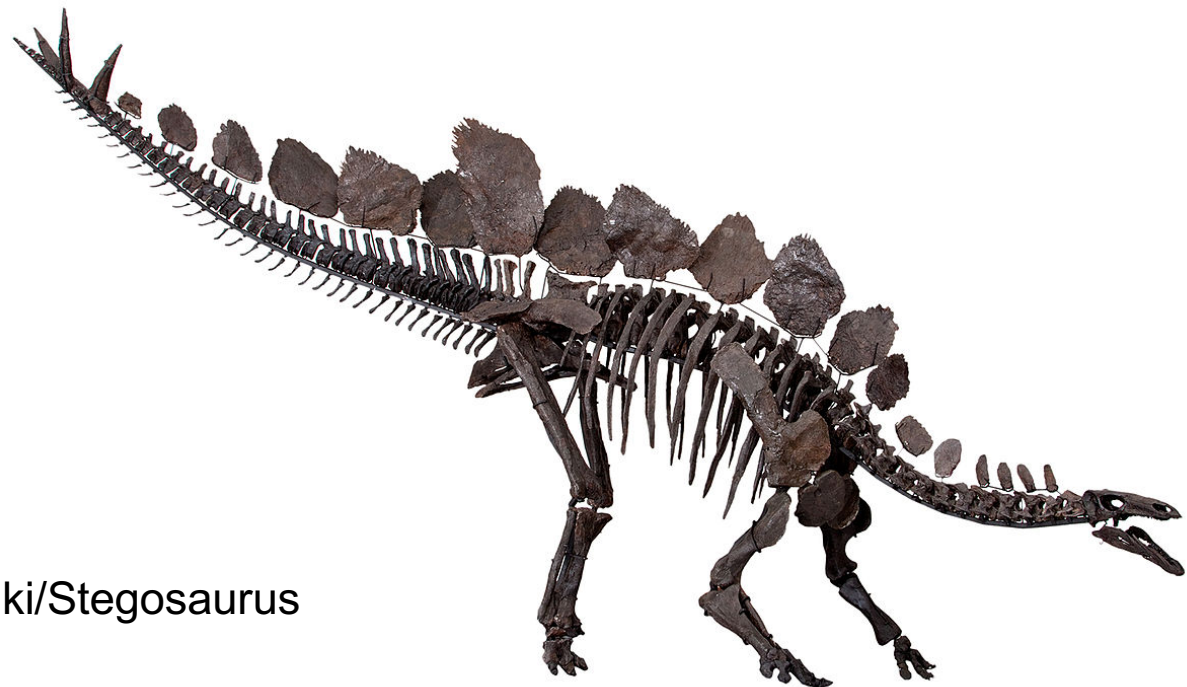
“ In the name of security, Santiago Calatrava's bird has grown a beak. Its ribs have doubled in number and its wings have lost their interstices of glass.... [T]he main transit hall, between Church and Greenwich Streets, will almost certainly lose some of its delicate quality, while gaining structural expressiveness. It may now evoke a slender *stegosaurus* more than it does a bird.<sup>[45]</sup> ”

# Stegosaurus

From Wikipedia, the free encyclopedia

For the *pachycephalosaurid* of a similar name, see *Stegoceras*.

**Stegosaurus** (/ˈstɛɡəˈsɔːrəs/<sup>[1]</sup>) is a genus of armored dinosaur. Fossils of this genus date to the Late Jurassic period, where they are found in Kimmeridgian to early Tithonian aged strata, between 155 and 150 million years ago, in the western United States and Portugal. Several



Source: <https://en.wikipedia.org/wiki/Stegosaurus>

Susannah Maidment et al. & Natural History Museum, London - Maidment SCR, Brassey C, Barrett PM (2015) The Postcranial Skeleton of an Exceptionally Complete Individual of the Plated Dinosaur *Stegosaurus stenops* (Dinosauria: Thyreophora) from the Upper Jurassic Morrison Formation of Wyoming, U.S.A. PLoS ONE 10(10): e0138352. doi:10.1371/journal.pone.0138352

# Design Constraints: Noone is Immune

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However, Calatrava's original soaring spike design was scaled back because of security issues. The *New York Times* observed in 2005:

“ In the name of security, Santiago Calatrava's bird has grown a beak. Its ribs have doubled in number and its wings have lost their interstices of glass.... [T]he main transit hall, between Church and Greenwich Streets, will almost certainly lose some of its delicate quality, while gaining structural expressiveness. It may now evoke a slender *stegosaurus* more than it does a bird.<sup>[45]</sup> ”

The design was further modified in 2008 to eliminate the opening and closing roof mechanism because of budget and space constraints.<sup>[46]</sup>

The Transportation Hub has been dubbed "the world's most expensive transportation hub" for its massive cost for reconstruction—\$3.74 billion dollars.<sup>[48][58]</sup> By contrast, the proposed two-mile PATH extension



The lecture was slightly different  
While Prof. Mutlu was at CMU



# What Is This?





# Answer: Masterpiece of A Famous Architect

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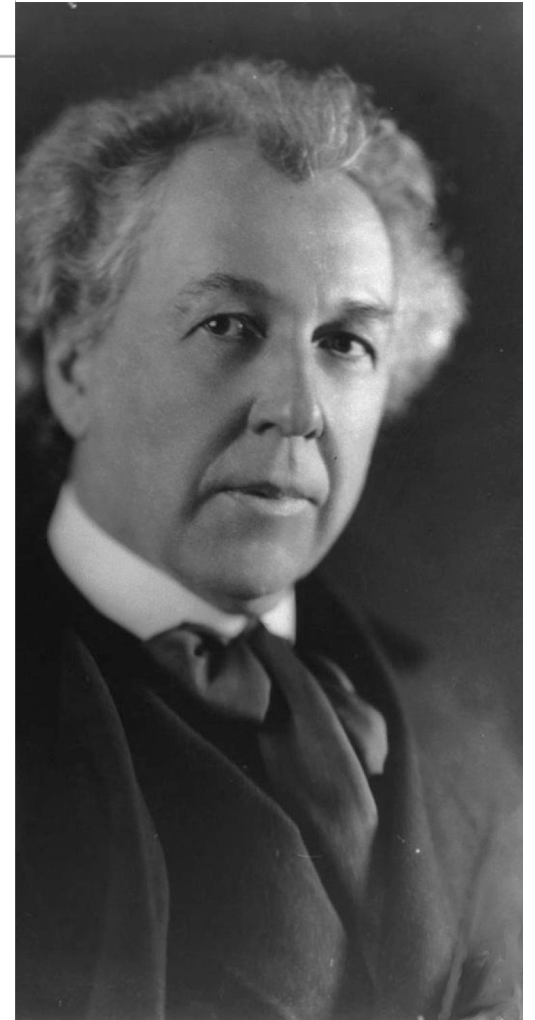
## Fallingwater

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From Wikipedia, the free encyclopedia

**Fallingwater** or **Kaufmann Residence** is a house designed by architect [Frank Lloyd Wright](#) in 1935 in rural [southwestern Pennsylvania](#), 43 miles (69 km) southeast of [Pittsburgh](#).<sup>[4]</sup> The home was built partly over a waterfall on [Bear Run](#) in the Mill Run section of [Stewart Township, Fayette County, Pennsylvania](#), in the [Laurel Highlands](#) of the [Allegheny Mountains](#).

*Time* cited it after its completion as Wright's "most beautiful job";<sup>[5]</sup> it is listed among *Smithsonian's* Life List of 28 places "to visit before you die."<sup>[6]</sup> It was designated a [National Historic Landmark](#) in 1966.<sup>[3]</sup> In 1991, members of the [American Institute of Architects](#) named the house the "best all-time work of American architecture" and in 2007, it was ranked twenty-ninth on the [list of America's Favorite Architecture](#) according to the AIA.





# Find The Differences of This and That

# This

---





# That

---





# A Key Question

---

- How was Wright able to design his masterpiece?
- Can have many guesses
  - ❑ (Ultra) hard work, perseverance, dedication (over decades)
  - ❑ Experience
  - ❑ Creativity, Out-of-the-box thinking
  - ❑ A good understanding of past designs
  - ❑ Good judgment and intuition
  - ❑ Strong skill combination (math, architecture, art, engineering, ...)
  - ❑ Funding (\$\$\$\$), luck, initiative, entrepreneurialism
  - ❑ Strong understanding of and commitment to fundamentals
  - ❑ Principled design
  - ❑ ...
- (You will be exposed to and hopefully develop/enhance many of these skills in this course)

# A Quote from The Architect Himself

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- “architecture [...] based upon **principle**, and not upon **precedent**”





# A Principled Design

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## Organic architecture

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From Wikipedia, the free encyclopedia

**Organic architecture** is a [philosophy](#) of [architecture](#) which promotes harmony between human habitation and the natural world through design approaches so sympathetic and well integrated with its site, that buildings, furnishings, and surroundings become part of a unified, interrelated composition.

A well-known example of organic architecture is [Fallingwater](#), the residence Frank Lloyd Wright designed for the Kaufmann family in rural Pennsylvania. Wright had many choices to locate a home on this large site, but chose to place the home directly over the waterfall and creek creating a close, yet noisy dialog with the rushing water and the steep site. The horizontal striations of stone masonry with daring [cantilevers](#) of colored beige concrete blend with native rock outcroppings and the wooded environment.



# A Key Question

---

- How was Wright able to design his masterpiece?
- Can have many guesses
  - ❑ (Ultra) hard work, perseverance, dedication (over decades)
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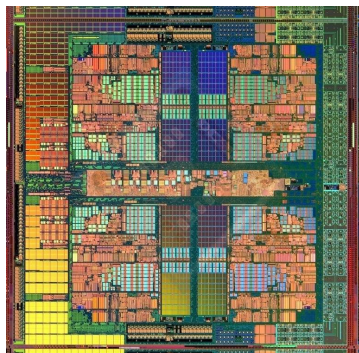
# Takeaways

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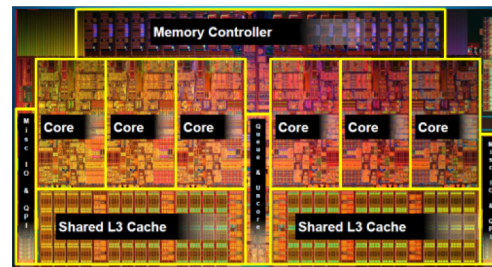
- It all starts from the basic building blocks and design principles
- And, knowledge of how to use & apply them
- Underlying technology might change (e.g., steel vs. wood)
  - but methods of taking advantage of technology bear resemblance
  - methods used for design depend on the principles employed

# The Same Applies to Processor Chips

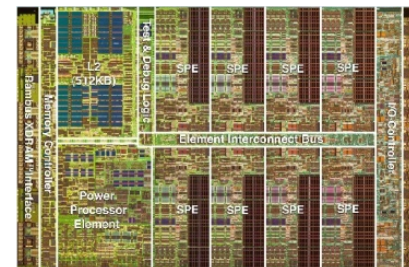
- There are basic building blocks and design principles



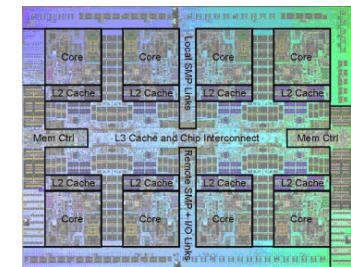
AMD Barcelona  
4 cores



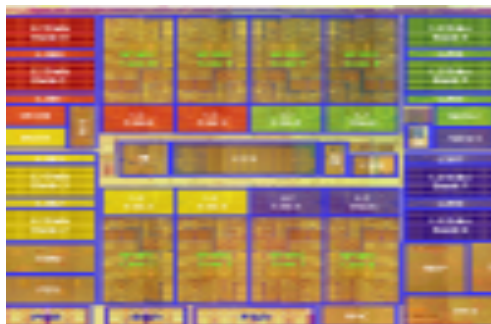
Intel Core i7  
8 cores



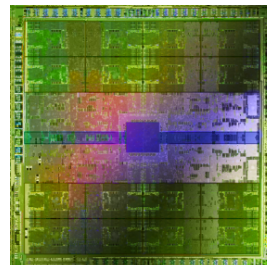
IBM Cell BE  
8+1 cores



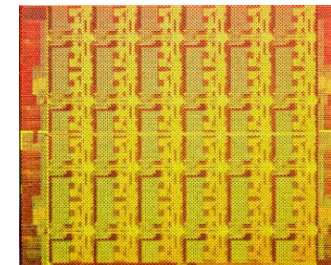
IBM POWER7  
8 cores



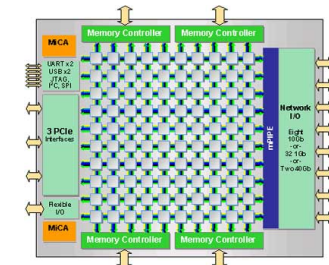
Sun Niagara II  
8 cores



Nvidia Fermi  
448 "cores"



Intel SCC  
48 cores, networked



Tiler TILE Gx  
100 cores, networked



# The Same Applies to Computing Systems

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- There are **basic building blocks** and **design principles**



# The Same Applies to Computing Systems

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- There are **basic building blocks** and **design principles**





# Different Platforms, Different Goals





# Different Platforms, Different Goals

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# Different Platforms, Different Goals

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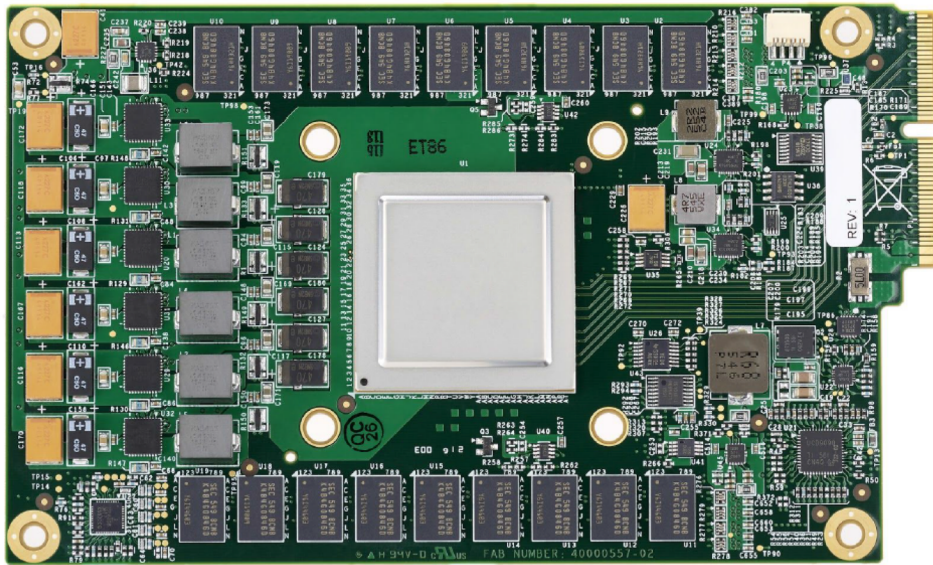
# Different Platforms, Different Goals

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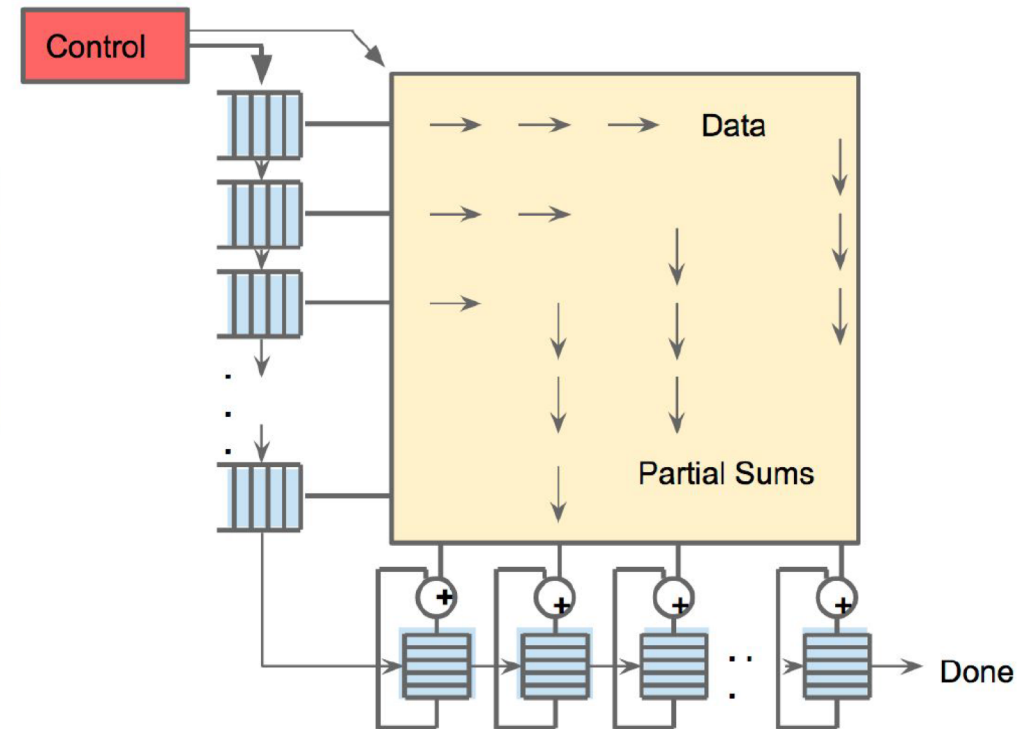




# Different Platforms, Different Goals



**Figure 3.** TPU Printed Circuit Board. It can be inserted in the slot for an SATA disk in a server, but the card uses PCIe Gen3 x16.



**Figure 4.** Systolic data flow of the Matrix Multiply Unit. Software has the illusion that each 256B input is read at once, and they instantly update one location of each of 256 accumulator RAMs.

Jouppi et al., “In-Datacenter Performance Analysis of a Tensor Processing Unit”, ISCA 2017.

# Basic Building Blocks

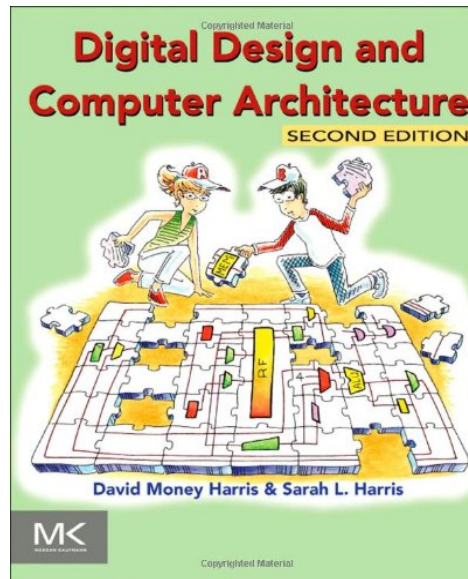
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- Electrons
- Transistors
- Logic Gates
- Combinational Logic Circuits
- Sequential Logic Circuits
  - Storage Elements and Memory
- ...
- Cores
- Caches
- Interconnect
- Memories
- ...

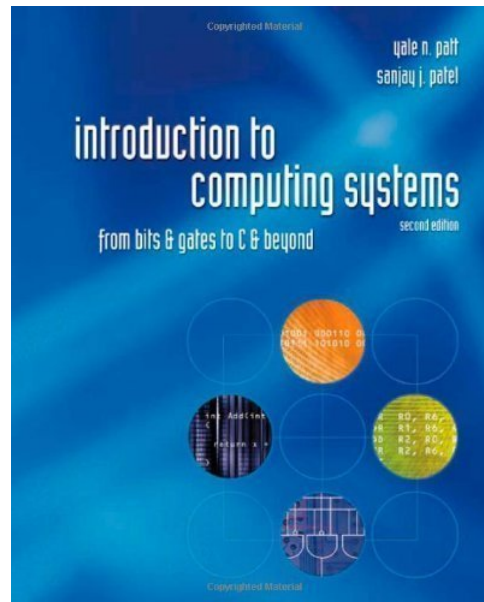
# Reading Assignments for This Week

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- Chapter 1 in Harris & Harris



- Chapters 1-2 in Patt and Patel



- Supplementary Lecture Slides on Binary Numbers



# Major High-Level Goals of This Course

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- In Digital Circuits & Computer Architecture
- Understand the basics
- Understand the principles (of design)
- Understand the precedents
- Based on such understanding:
  - learn how a modern computer works underneath
  - evaluate tradeoffs of different designs and ideas
  - implement a principled design (a simple microprocessor)
  - learn to systematically debug increasingly complex systems
  - Hopefully enable you to develop novel, out-of-the-box designs
- The focus is on basics, principles, precedents, and how to use them to create/implement good designs

# Why These Goals?

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- Because you are here for a Computer Science degree
- **Regardless of your future direction**, learning the principles of digital design & computer architecture will be useful to
  - ❑ design better hardware
  - ❑ design better software
  - ❑ design better systems
  - ❑ make better tradeoffs in design
  - ❑ understand why computers behave the way they do
  - ❑ solve problems better
  - ❑ think “in parallel”
  - ❑ think critically
  - ❑ ...

# Why Do We Have Computers?



# Why Do We Do Computing?

# To Solve Problems

# To Gain Insight



To Enable  
a Better Life & Future

# How Does a Computer Solve Problems?

# Orchestrating Electrons

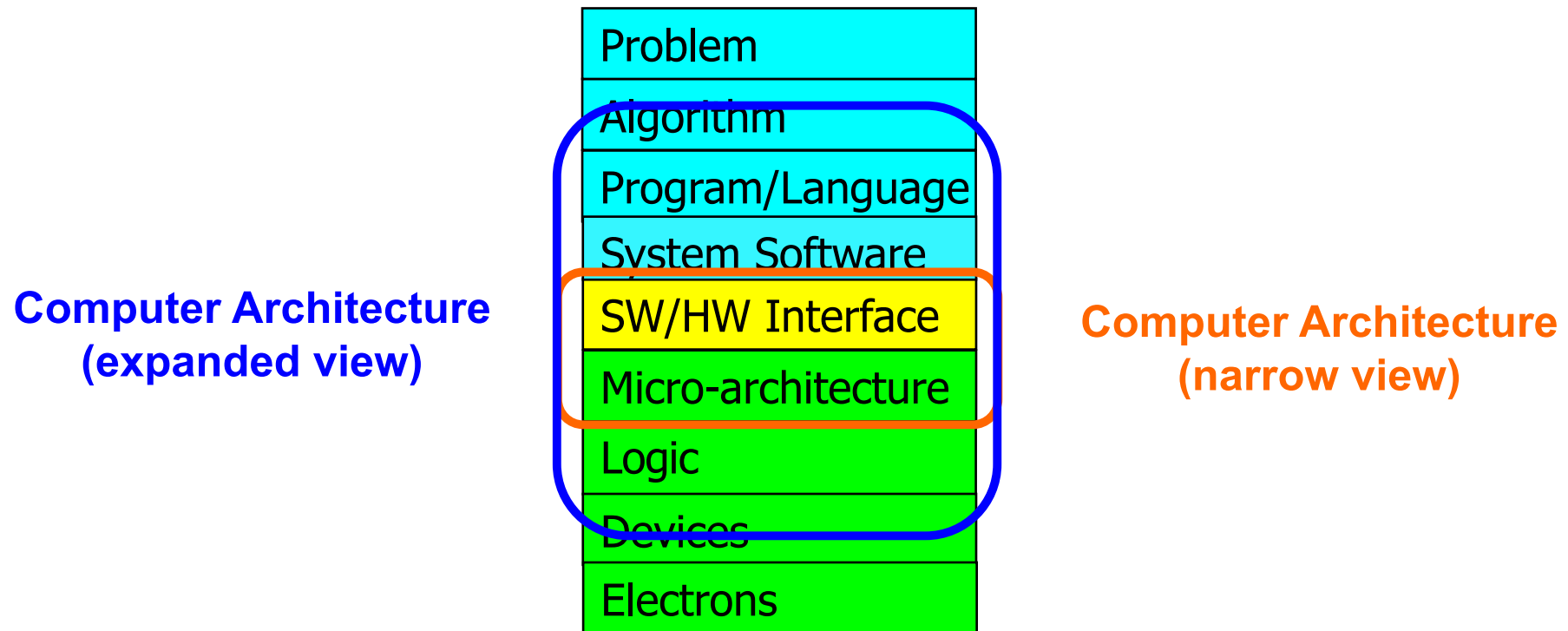
In today's dominant technologies



# How Do Problems Get Solved by Electrons?

# The Transformation Hierarchy

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# Levels of Transformation

“The purpose of computing is [to gain] insight” (*Richard Hamming*)  
*We gain and generate insight by solving problems*  
*How do we ensure problems are solved by electrons?*

## Algorithm

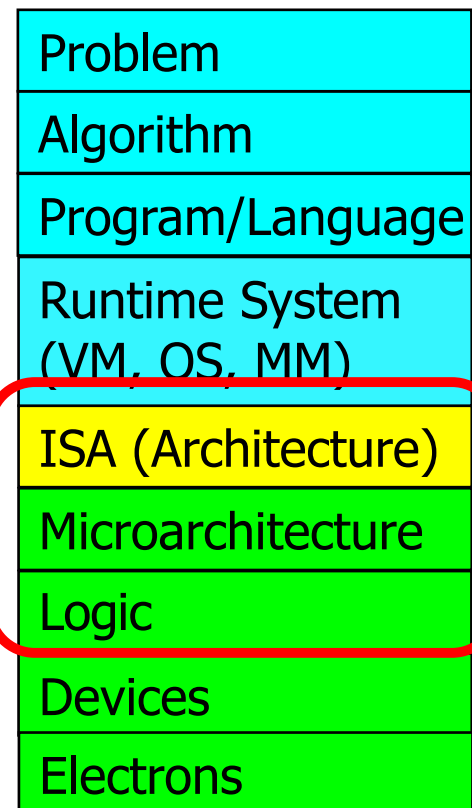
Step-by-step procedure that is **guaranteed to terminate** where **each step is precisely stated** and **can be carried out by a computer**

- **Finiteness**
- **Definiteness**
- **Effective computability**

Many algorithms for the same problem

## Microarchitecture

An implementation of the ISA



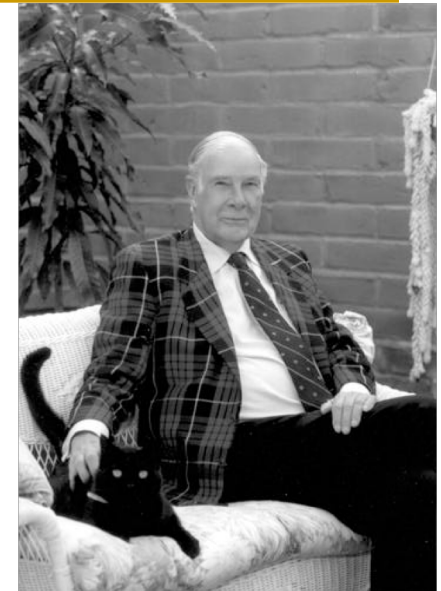
ISA  
(Instruction Set Architecture)

Interface/contract between  
SW and HW.

What the programmer  
assumes hardware will  
satisfy.

## Digital logic circuits

Building blocks of micro-arch (e.g., gates)





# Aside: A Famous Work By Hamming

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- Hamming, “Error Detecting and Error Correcting Codes,” Bell System Technical Journal 1950.
- Introduced the concept of Hamming distance
  - number of locations in which the corresponding symbols of two equal-length strings is different
- Developed a theory of codes used for error detection and correction
- Also see:
  - Hamming, “You and Your Research,” Talk at Bell Labs, 1986.
  - <http://www.cs.virginia.edu/~robins/YouAndYourResearch.html>

# Where to Get Up-to-date Course Info?

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- Website:

- <https://safari.ethz.ch/digitaltechnik/>
- Lecture slides and videos
- Readings
- Lab information
- Course schedule, handouts, FAQs
- Software
- Plus other useful information for the course
- Check frequently for announcements and due dates
- This is your single point of access to all resources

- Your ETH Email

- Lecturers and Teaching Assistants

# Lecture and Lab Times and Policies

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## ■ Lectures:

- Thursday and Fridays, 13:15-15:00
- HG F7 (F5 overflow)
- Attendance is for your benefit and is therefore important
- Some days, we will have guest lectures and exercise sessions

## ■ Lab sessions:

- See online
- You should definitely attend the lab sessions
  - In-class evaluation (70%) and mandatory lab reports (30%)
- Labs will start on March 5th
- Lab information and handouts are here:
  - <https://safari.ethz.ch/digitaltechnik/spring2019/doku.php?id=labs>



# Course Info: Instructor

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## ■ Onur Mutlu

- Professor @ ETH Zurich CS, since September 2015 (started May 2016)
- Strecker Professor @ Carnegie Mellon University ECE/CS, 2009-2016, 2016-...
- PhD from UT-Austin, worked at Google, VMware, Microsoft Research, Intel, AMD
- <https://people.inf.ethz.ch/omutlu/>
- [omutlu@gmail.com](mailto:omutlu@gmail.com) (Best way to reach Prof. Mutlu)
- Office hours: By appointment (email Prof. Mutlu)

## ■ Research and Teaching in:

- Computer architecture, computer systems, bioinformatics, hardware security
- Memory and storage systems
- Hardware security
- Fault tolerance
- Hardware/software cooperation
- Genome analysis and application-algorithm-hardware co-design
- ...

# Course Info: PhD Assistants

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- Head Assistant
  - Dr. Juan Gomez Luna
  
- Vice-Head Assistant
  - Hasan Hassan
  
- (Other) Key Assistants and Guest Lecturers
  - Dr. Mohammed Alser
  - Dr. Lois Orosa
  - Giray Yaglikci
  - Can Firtina

# Course Info: Student Assistants

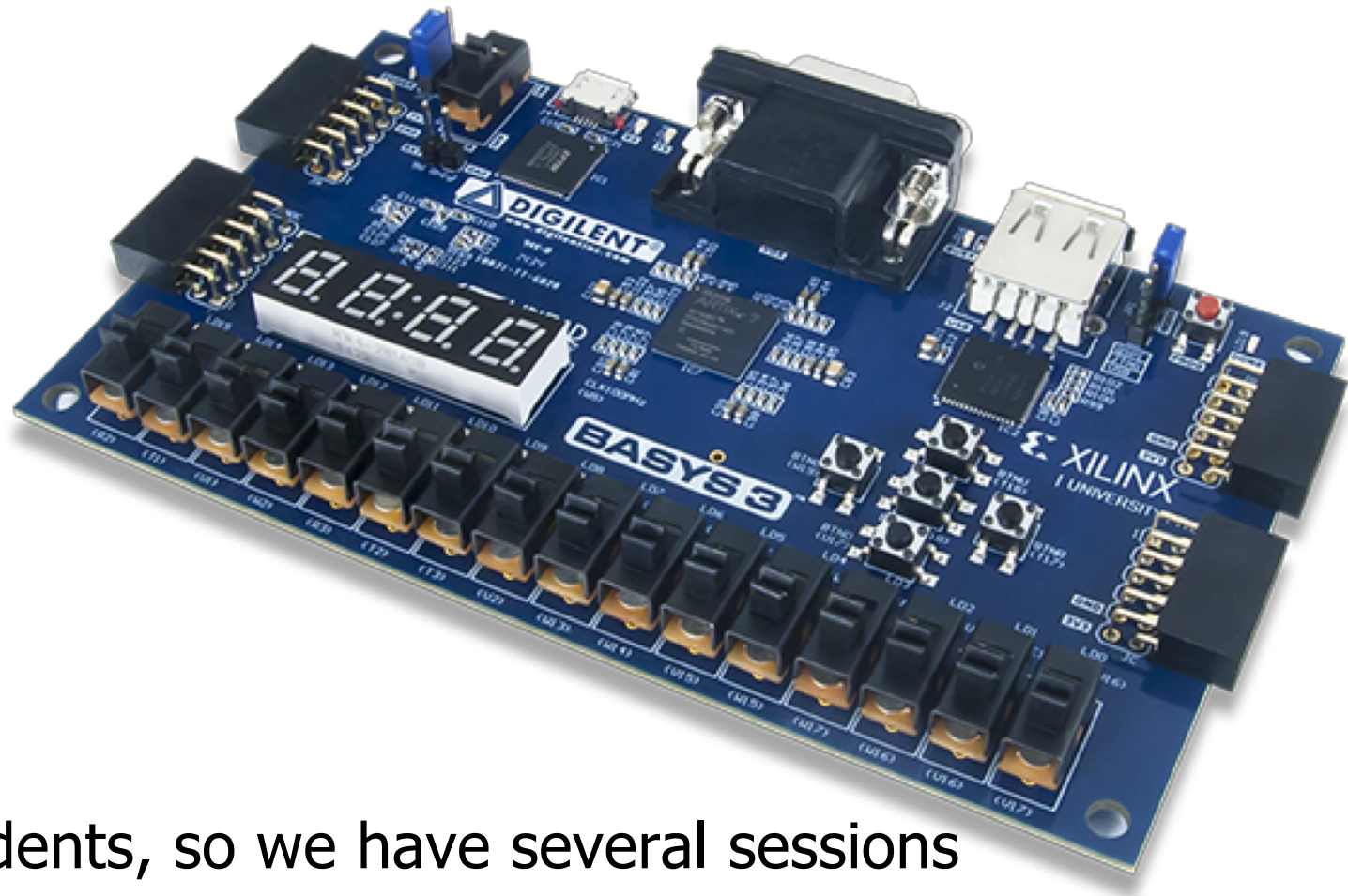
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- Alexander Breuss
- Salomon Brulisauer
- Sven Gregorio
- Lukas Gygi
- Leo Horné
- Gabriela Krasnopolaska
- Lara Lazier
- Nika Mansouri
- Artur Melo
- Chris Mnuk
- Johannes Schenk
- Roberto Starc



# We have some great lab sessions

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- Many students, so we have several sessions
  - Tuesday 15-17
  - Friday 8-10
  - Wednesday 15-17
  - Friday 10-12

# High Level Labs Summary

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- At the end of the exercises, we will have built a 32-bit microprocessor running on the FPGA board
  - It will be a small processor, but it will be able to execute small programs
- Each week we will have a new exercise
  - Not all exercises will require the FPGA board
- You are encouraged to experiment with on your own
  - We may have some extra boards for those who are interested
  - **It is not possible to destroy the board by programming!**
- Next week we have a lecture with more on the exercises

# Lab Organization (first Lab March 5<sup>th</sup>)

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## ■ Groups

- Choose your preferred group in Moodle
  - <https://moodle-app2.let.ethz.ch/mod/choicegroup/view.php?id=334642>
  - Due 24.02.2019 at 2:00pm
- Choose your partner
  - <https://goo.gl/bn2v3i>
  - Due 01.03.2019 at 11:59pm

## ■ Lab grades from previous years

- <https://moodle-app2.let.ethz.ch/mod/choice/view.php?id=334643>
- Choose among (due 01.03.2019 at 11:59pm):
  - 1) I will use my lab grades from previous years, and I won't do the labs this year
  - 2) I will use my lab grades from previous years, but I will do the labs this year
  - 3) I won't use my lab grades from previous years. I will do the labs this year
- If 1) or 2), we will scale your lab grades to the points that correspond to in-class evaluation

# Final Exam

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- 180-minute written exam as part of the session
- Rules (from the course catalogue)
  - 70% of your final grade (the rest comes from exercises)
  - No books, computer, mobile phones, calculators etc. allowed
  - Six A4 pages with handwritten notes are allowed
  - Exam will be available in **German** (and English)
    - There will be a survey of who wants to have which version ahead of the exam.
- Previous exams available online:
  - <https://safari.ethz.ch/digitaltechnik/spring2019/doku.php?id=exams>
- Exam questions are similar to questions in **Optional HWs**
  - Optional HWs are **highly recommended**



# If You Need Help

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- Post your question on Moodle Q&A Forum
  - **Preferred** for **technical** questions
- Write an e-mail to:
  - [digitaltechnik@lists.inf.ethz.ch](mailto:digitaltechnik@lists.inf.ethz.ch)
  - The instructor and all assistants will receive this e-mail

# Design of Digital Circuits

## Lecture 1: Introduction and Basics

Prof. Onur Mutlu

ETH Zurich

Spring 2019

21 February 2019

Tomorrow: We take a deeper  
look at 4 mysteries

# Four Mysteries: Familiar with Any?

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- Meltdown & Spectre (2017-2018)
- Rowhammer (2012-2014)
- Memory Performance Attacks (2006-2007)
- Memories Forget: Refresh (2011-2012)